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Relevance of similitude parameters for drag reduction in sport aerodynamics

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Abstract

It is possible to improve the aerodynamics of an athlete by influencing the location at which the boundary layer transition occurs on the body. The state of the boundary layer and therefore the drag coefficient depend mainly, in the critical Reynolds number range, on the shape, the aspect ratio and the 3-dimensionality of the body, the fabric properties and the wind turbulence. When planning a wind tunnel experiment, some of these factors are sometimes neglected. In this research, it was observed that each parameter was relevant and had a relatively large impact on the drag coefficient. Wind-tunnel tests on a 1:1 scale mannequin of an elite athlete were conducted in a fully controlled environment. They allowed the proper representation of the body proportions and cross-section dimensions as well as the 3-dimensionality aspect. It was observed that the flow interaction between the limbs dictated which fabric provided the lowest drag for each part of the body for a desired range of wind speed. An inappropriate simulation of the conditions can optimise the drag reduction for an erroneously targeted Reynolds number range. The research provided a quantitative evaluation of the relevance of correctly simulating parameters for drag reduction in sport aerodynamics.

Keywords: Bluff body aerodynamics; Wind tunnel; Critical Reynolds number; Drag; Boundary layer transition; Aspect ratio, 3-Dimensionality; Wind turbulence; Surface roughness

1. Introduction

Given optimal physical shape and biomechanical position that can generate maximum momentum, the main parameter that can reduce race time considerably is the aerodynamics of the athlete and his or her equipment. The total drag experienced by the athlete is divided into two components: friction drag and pressure drag. The friction drag results from the friction between the air and the athlete and is represented by a viscous boundary layer at the surface of the athlete's garment. The pressure drag results from the difference in pressure between the windward and

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leeward area of the athlete along the direction of the flow. When separation of the shear layer occurs, pressure drag dominates over friction drag which defines the 'bluff body' aerodynamics category.

The circular cylinder is one of the most common bluff body shapes with round edges. Cylinder aerodynamics has received a lot of attention from researchers for decades, yet remains inadequately understood. The three main aerodynamic regimes as denoted by where the transition from laminar to turbulent flow occurs have been described in detail in Zdravkovich [1]. At low Reynolds number, the transition happens in the wake, TrW, then the transition moves forward to the shear layer, TrSL, and by increasing the Reynolds number up to $1x10^5$, the transition takes place in the boundary layer, TrBL, where an important reduction of the drag is observed which defines the critical Reynolds number range for a circular cylinder. The left side of Figure 1 shows the aerodynamic force coefficients and especially the drag coefficient (C_D) as a function of Reynolds number for a smooth circular cylinder with the three distinct regimes and the important drag reduction in the TrBL regime.

Surface pressure distribution around a circular cylinder in the critical Reynolds number range have shown that the reduction in drag was associated with an asymmetrical pressure distribution which is caused by the formation of a laminar separation bubble on one side of the cylinder that generates a large zone of suction and a reduced base pressure (TrBL1). The transition from laminar to turbulent flow in the separated shear layer allows the latter to reattach to the body. With a slightly higher Reynolds number, the minimum drag is achieved and the pressure distribution is characterised by the appearance of a separation bubble on each side of the cylinder creating two large symmetric lobes of suction with a very small base pressure (TrBL2). The right side of Figure 1 shows the surface pressure distribution around the cross-section in the critical Reynolds number range. Surface pressure distribution for a vertical, an inclined and a yawed cylinder in the critical Reynolds number range have been investigated more recently by Larose et al. and Zan and Matsuda [2, 3, 4]. They have observed similar distributions of surface pressure for a smooth static circular cylinder in a smooth cross-flow, but with important variations for other conditions.

Reduction of the drag coefficient can be an advantage and has been employed in many sports. Pioneering research by Brownlie [5], followed by others thereafter, focused on this aspect through an innovative study of the aerodynamic characteristics of sports apparel with the help of cylinders and live athletes. The speed at which the athlete is racing, the fluid density and the characteristic dimension of the human body, which can be approximated as a combination of multiple circular cylinders, define a Reynolds number that can be in the critical range. Depending on the body shape and proportion, the velocity, the free-stream turbulence and the surface roughness of the fabric covering the athlete, the drag area coefficient can be reduced to a minimum value. Since all these parameters affect the drag, they have to be simulated correctly in a wind tunnel in order to optimise the reduction of the drag for the desired range of speed. This research intended to simulate correctly all those parameters and to evaluate their impact on the optimization of the drag reduction.

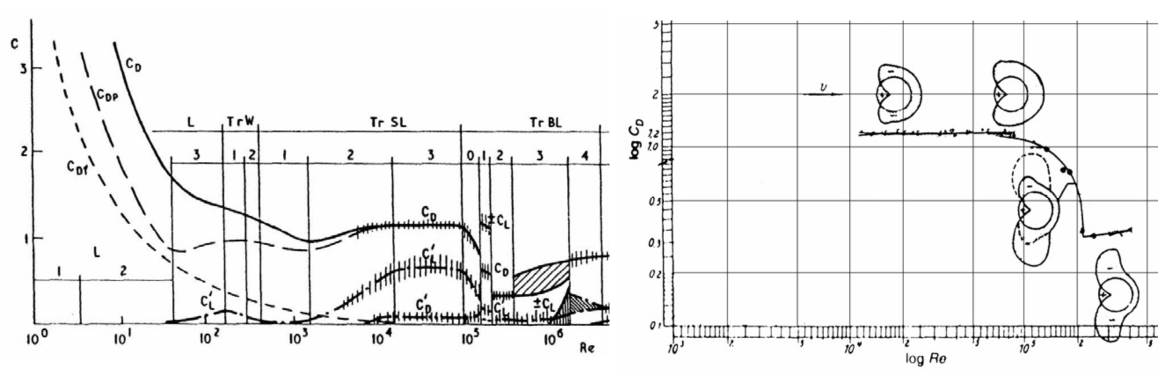

Figure 1. Aerodynamic force coefficients versus Reynolds number for a smooth circular cylinder (left) and surface pressure distribution for a circular cross-section in the critical Reynolds number range (right), adapted from Zdravkovich [1].

2. Experimental conditions

In order to optimize correctly the drag reduction of a human body shape, a 1:1 scale mannequin of an athlete in a sidepush skating position was made and tested in the NRC 2m x 3m Wind Tunnel. The mannequin allowed simulation of the appropriate body proportions and cross-sectional dimensions that are typical for an athlete. Figure 2 shows the mannequin installed in the test section of the wind tunnel as well as cross-sections normal to the main axis of the right leg and right arm for: calf, knee, thigh, upper arm.

The mannequin was mounted on an external balance that measured the overall drag force. The mannequin was also instrumented to measure surface pressure at strategic locations that can be integrated to obtain a local force on the body. The location of the rings of surface pressure taps is presented on Figure 2 for the right leg and the right upper arm. Tests were done for a range of wind speeds from 30 to 65 km/h. The mannequin was dressed with different suits or parts of suits with a large variety of surface roughness. Finally, tests were done for two different flow conditions; laminar and turbulent.

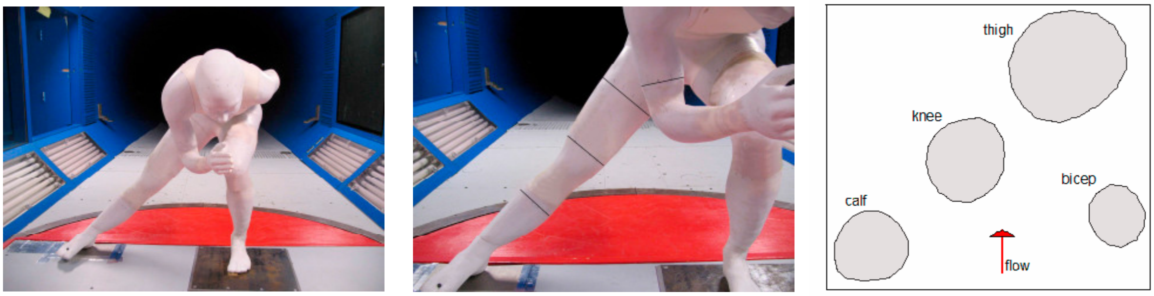

Figure 2. Mannequin in a sidepush position installed in the test section of the NRC's 2m x 3m Wind Tunnel (left) and the four cross-sections normal to the main axis where rings of surface pressure holes were located (right leg and arm).

3. Results

3.1. Aspect ratio, 3-dimensionality, body proportions

As a first approximation, the human body legs and arms are often considered as circular cylinders and optimization of drag reduction is often done in a wind tunnel using a circular cylinder that represents, for example, the lower leg. The circular cylinder can be long compared to its diameter which increases its aspect ratio and make a 2D flow study or, the circular cylinder can be short with a length running from ankle to above knee and is characterized by a 3D flow. In both cases, the flow developing around the circular cylinder does not simulate properly the 3D flow and the interaction of the flow around the multiple limbs of the body. Using a mannequin with a 1:1 scale ensures an accurate simulation of the aspect ratio and 3-dimensionality that characterize the flow around the human body. It also gives a better modeling of the cross-section of each limb as the cross-section is not a perfect circle but changes shape and dimension along the main axis.

Figure 3 (right side) presents the cross-section view along the main axis for the right thigh, knee and calf as well as the right upper arm for a smooth fabric in a laminar flow. The distribution of the surface pressure coefficient is shown with the blue line (outside the cross-section) as suction and red line as positive pressure (inside the cross-section). The solid magenta line is the data corresponding to a wind speed of 48.9 km/h and the dotted black line for a wind speed of 58.7 km/h. It is clear that for the same diameter (maximum width) at the calf and above knee cross-sections, the surface pressure coefficient distribution was different at 58.7 km/h. The calf was entering in the 1-bubble regime (TrBL1) while the knee was not. The flow prevailing around the knee was affected by the flow from the thigh and from the calf which delayed the transition of the boundary layer from laminar to turbulent. A stand alone circular cylinder could not have captured this aerodynamic phenomenon. The left side of Figure 3 presents the overall drag area coefficient measured by the external balance. For the case with smooth fabric in smooth flow (black line), there was a reduction in drag shown by the change of slope between 50 and 60 km/h which is consistent with the surface pressure distribution with the 1-bubble regime (TrBL1) present on the calf that is associated with a reduction of drag. It was also observed that the right calf was entering into the 2-bubble regime (TrBL2) at 75 km/h while the right thigh was entering the 1-bubble regime (TrBL1).

Theoretically, it would have been expected that the thigh which has a larger diameter than the right calf would have the transition at lower wind speed than the calf. However, the thigh is exposed to a different upcoming flow than the right calf with the arm being upstream of the upper leg and closer to the left upper leg. The 3D flow that develops around the right thigh was definitely not the same as the one around a circular cylinder with the same diameter, standing alone in the flow. The local velocity on the thigh is not only affected by the geometry of the cross-section but also by the interaction with the flow or vortices shed from the other nearby parts of the body. It is clear that the optimization of the drag reduction for a human body has to be done with the whole body modelled to capture the entire flow picture and flow interactions that take place around the human body.

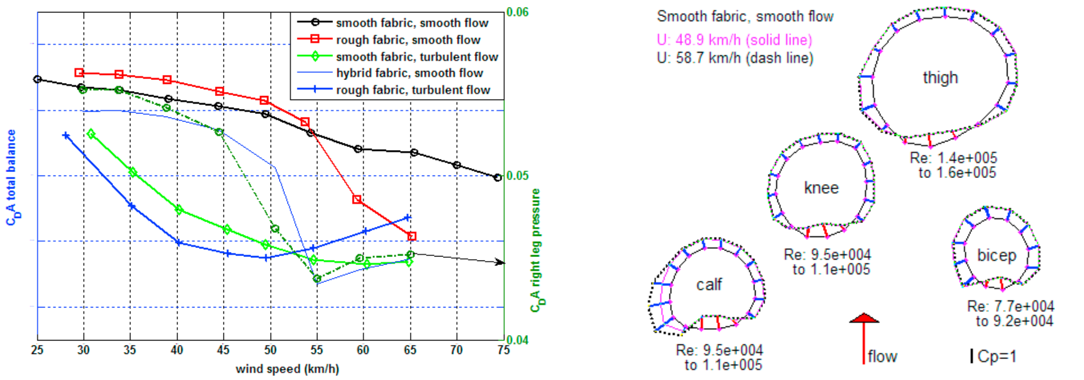

Figure 3. Left: Drag area coefficient measured with the external balance for five different conditions and from integration of surface pressure (dash line) of the right leg for the hybrid fabric, smooth flow condition. Right: Distribution of surface pressure coefficient for a smooth fabric in smooth flow at 48.9 km/h (solid magenta line) and 58.7 km/h (dotted black line).

3.2. Surface roughness of the fabric

Another parameter investigated was the surface roughness of the fabric used to make the tight clothing of the athlete. Skinsuits with smooth, rough and hybrid fabrics were used to dress the mannequin. Figure 4 shows the distribution of the surface pressure coefficient for a rough fabric on the left and a hybrid fabric (smooth and rough) on the right. The distribution of surface pressure coefficient shows clearly that the right leg was in the 1-bubble regime (TrBL1) between 48.8 and 58.6 km/h for the rough fabric while for the smooth fabric (Figure 3), the 1-bubble regime was only present for the calf. The higher surface roughness promoted the transition to occur at lower wind speed. If the fabric was used on a circular cylinder, it would not have been expected that the thigh and the calf be in the same aerodynamic regime since they do not have the same diameter (maximum width). For the smooth fabric, at 75.5 km/h, the overall drag was still decreasing with the right calf at the end of the 1-bubble regime and starting the 2-bubble regime.

The right side of Figure 4 presents the surface pressure coefficient distribution for the hybrid suit with a rough fabric on the lower legs and arms and smooth fabric for the rest of the body. It is clear that the rough fabric promoted the transition on the right bicep which affected the flow seen by the thigh. The right calf and the right knee were at the end of the 2-bubble regime (TrBL2) with a smaller suction in the lobes at 64.5 km/h. It is also interesting to note the size of the lobes of suction for the right calf compared to the right knee. The right calf contributed significantly to the drag reduction compared to the right knee even if both experienced transition from laminar to turbulent. The left side of Figure 3 shows the drag area coefficient of the right leg based on the integration of the surface pressure coefficients for the three rings (dash line). It corresponded well with the total drag area coefficient measured by the external balance for the entire body. The transition that occurs on the right leg is a key element for the behaviour of the overall aerodynamics of the model.

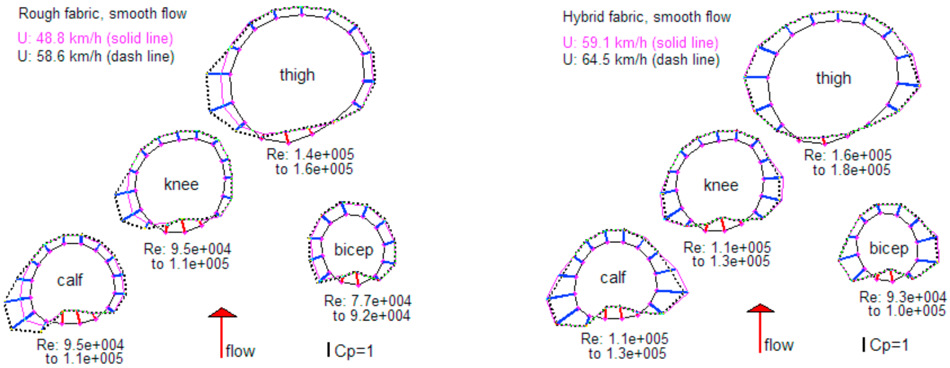

Figure 4. Left: Distribution of surface pressure coefficient for four different cross-sections for a rough fabric in smooth flow at 48.8 km/h (solid magenta line) and 58.6 km/h (dotted black line). Right: Distribution of surface pressure coefficient for a hybrid skinsuit with smooth/rough fabrics, in smooth flow at 59.1 km/h (solid magenta line) and 64.5 km/h (dotted black line).

3.3. Free-stream turbulence

The free-stream turbulence is also an important parameter that affects the drag area coefficient. Tests with the mannequin dressed with smooth and with rough fabrics and exposed to turbulent flow were carried out. The turbulent flow simulated in the wind tunnel was representative of the flow experienced by a speed skater when racing on an oval. Figure 5 shows the distribution of surface pressure coefficient measured on the right leg and on the bicep in the turbulent flow condition. For smooth and rough fabrics, the four cross-sections were promoted to the 2-bubble regime (TrBL2) and the total drag area coefficients measured with the external balance were smaller than the one measured in smooth flow (Figure 3).

For the smooth fabric in an appropriate free-stream turbulent flow, the minimum drag was reached at 60 km/h and corresponded well with the end of the 2-bubble regime (TrBL2) on the right leg and bicep (see the left side of Figure 5). If the test had been done only in smooth flow, the fabric would not be the optimal one for a drag reduction at 60 km/h since it was still in the beginning of the 1-bubble regime (TrBL1) and would reach its minimum value at a higher wind speed. The comparison of the drag area coefficient for a smooth fabric in smooth and turbulent flows indicated that there was a difference of at least 20 km/h between the wind speeds at which the minimum drag occurred considering the intensities of flow turbulence that the model was exposed to in this study. For a rough fabric in turbulent flow, the surface pressure distribution on the right side of Figure 5 shows that at 49.1 km/h the right leg was already at the end of the 2-bubble regime (TrBL2) and increasing the wind speed to 64.1 km/h promoted a reduction of the suction in the two lobes and an increase of the suction in the base pressure (TrBL3 regime). This was consistent with the overall increase in drag that can be observed on the left side of Figure 3 (blue line with '+' marker) .

Simulating the appropriate flow turbulence is crucial to optimise the drag reduction for the targeted Reynolds number range or wind speed. If the simulation of the appropriate flow turbulence is not considered properly, it is possible to tune the drag reduction of the sport apparel for the wind tunnel flow conditions instead of for the field-of-play conditions.

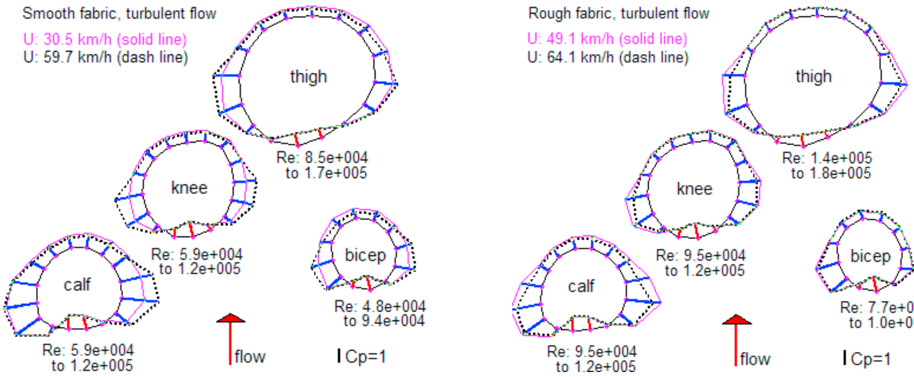

Figure 5. Left: Distribution of surface pressure coefficient for four different cross-sections for a smooth fabric in turbulent flow at 30.5 km/h (solid magenta line) and 59.7 km/h (dotted black line). Right: Distribution of surface pressure coefficient for a rough fabric in turbulent flow at 49.1 km/h (solid magenta line) and 64.1 km/h (dotted black line).

4. Conclusions

This research contributed to create a unique compendium of data for the aerodynamics of a human body by taking into account and simulating properly the parameters that affect the aerodynamic drag; specifically in the critical Reynolds number range. The overall drag area coefficient provided the picture of the whole body drag force reduction. The local measurement of the drag using surface pressure was an asset to help understand the state of the boundary layer and the aerodynamic regime for each section of the body in order to optimize the overall drag reduction. It has been demonstrated that the flow that developed around the 3D human body shape was subject to interactions between the nearest limbs and the aerodynamics should therefore not be simplified to a combination of circular cylinders without correction. The 3D flow, the flow interactions between parts of the body, the surface roughness of the fabric and the flow turbulence are all parameters that affected the range of wind speed at which the minimum drag occurred. The knowledge of the aerodynamics of a basic circular cylinder shape has helped to understand the parameters that affect the aerodynamic drag in the critical Reynolds number range and the possibilities of efficiently using those ones to the advantage of an athlete. However, there are some limitations to the parallel that can be drawn between circular cylinders and the 3D human body and an appropriate simulation of the shape and the flow turbulence is crucial to obtain meaningful results with regards to drag reduction for an athlete.

Acknowledgements

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